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TRANSPORTABLE CALIBRATION PADS FOR GROUND AND AIRBORNE GAMMA-RAY SPECTROMETERS

R.L. Grasty, P.B. Holman, and Y.B. Blanchard

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Cover description

Calibrating a portable gamma-ray spectrometer on the transportable pads. The Geological Survey of Canada Skyvan aircraft is in the background. GSC 1991-123

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CONTENTS

1 Abstract/Résumé

1 Introduction

2 Design of portable gamma-ray spectrometer calibration pads
2 Dimensions
3 Ideal concentrations

4 Construction of transportable pads
4 Raw materials
6 Preparation of materials
7 Construction procedures

8 Pad concentrations
8 Sampling and analyses
8 Homogeneity tests and grade assignments

10 Calibration of portable spectrometers — theory
10 The conversion equations for a portable spectrometer
12 Geometry correction
13 Calibration equations

13 Calibration of portable spectrometers — practice

15 Comparison of transportable and aircraft calibration pads
15 Principles of aircraft calibration
15 Measurements on Uplands pads
16 Experiments with transportable calibration pads
18 Aircraft calibration — practice

19 Radiation dose due to transportable pads
19 Terminology and dose relationships
20 Dose calculations

20 Summary and conclusions

21 References

Appendices

22 A. Computation of calibration factors (matrix method)
23 B. Hewlett-Packard 15-C program to calibrate a portable spectrometer on the transportable pads
24 C. Specifications of transportable pads
25 D. Program PADWIN

Tables

2 1. Response of a typical portable spectrometer to pads of different diameter
4 2. Ideal pad concentrations
5 3. Laboratory analyses and homogeneity measurements of first set of uranium pads
5 4. Results of sealing uranium pad U1 with polyester resin
6 5. Analysis of pad materials
9 6. Portable spectrometer total count homogeneity measurements
10 7. Analyses of mini-pad concrete samples
10 8. Assigned pad concentrations
12 9. Parameters used to calculate percentage of infinite source
12 10. Percentage of infinite source and geometric correction factors for transportable pads

14 | 11. Typical window sensitivities and stripping ratios for a 3 inch x 3 inch portable spectrometer
15 | 12. Original core sample laboratory analyses of Uplands pads
15 | 13. Portable spectrometer analyses of Uplands pads
16 | 14. Stripping ratios and sensitivities of box 1
17 | 15. Comparison of stripping ratios using Uplands pads and mini-pads
18 | 16. Comparison of stripping ratios for Box 2 with thin sources below and offset
18 | 17. Stripping ratios for Box 2 with transportable pads below and offset
19 | 18. Stripping ratios of Box 1 on a trolley and in the Skyvan

Figures

2 | 1. Response of a typical portable gamma-ray spectrometer to gamma radiation from 50 cm thick cylindrical pads of different diameter
3 | 2. Response of a typical portable gamma-ray spectrometer to gamma radiation from cylindrical pads of different diameter and thickness with a fixed weight of 675 kg
3 | 3. Response of a typical portable gamma-ray spectrometer to 2.62 MeV gamma radiation for optimum cylindrical pads of different weight
6 | 4. Portable gamma-ray spectrometer total counts from a concrete block manufactured from phosphate slag
6 | 5. The feldspar after crushing to pass a 20 mm sieve
7 | 6. The metal forms used for pad construction
7 | 7. Phosphate slag being loaded into the cement truck
8 | 8. Feldspar being loaded into the cement truck
8 | 9. Concrete samples being taken for later analysis
9 | 10. Homogeneity tests with lead-shielded spectrometer
12 | 11. Variation of geometric correction factors with detector elevation for the transportable pads
14 | 12. A portable spectrometer being calibrated
16 | 13. Calibration of one detector package

TRANSPORTABLE CALIBRATION PADS FOR GROUND AND AIRBORNE GAMMA-RAY SPECTROMETERS

Abstract

Sets of four transportable concrete pads 1 m x 1 m x 30 cm and weighing approximately 675 kg were constructed for calibrating portable gamma-ray spectrometers. Each set consists of a low radioactivity background pad, and three radioelement pads of potassium, uranium, and thorium which provide almost pure gamma-ray spectra. The potassium pads were manufactured using potassium feldspar and the thorium pads using britholite, a thorium-rich rare earth phosphate. Initial problems of radon loss from the uranium pad were overcome by using a uranium-rich slag of calcium silicate which was a byproduct from a phosphorus processing plant.

Experiments with these small pads have shown that they give the same potassium, uranium, and thorium spectral shapes as the much larger aircraft calibration pads. These small transportable pads can therefore be used for calibrating large volume airborne systems as well as portable gamma-ray spectrometers.

Résumé

On a construit des ensembles de 4 dalles de béton transportables, mesurant 1 m sur 1 m sur 30 cm et pesant environ 675 kg, pour l'étalonnage de spectromètres gamma. Chaque ensemble comporte une dalle de fond à radioactivité faible ainsi que 3 dalles à radioéléments de potassium, d'uranium et de thorium qui fournissent un spectre composé presqu'uniquement de rayons gamma. Les dalles de potassium se composent de feldspath potassique et les dalles à thorium, de britholite, un phosphate de terres rares riche en thorium. On a résolu les problèmes de perte de radon en utilisant une crasse riche en uranium de silicate de calcium qui est un sous-produit d'une usine de fabrication du phosphore.

L'essai de ces petites dalles a révélé qu'elles donnent les mêmes formes spectrales du potassium, de l'uranium et du thorium que les dalles d'étalonnage beaucoup plus grandes qui sont montées à bord d'aéronefs. Les petites dalles transportables peuvent donc servir pour l'étalonnage tant des systèmes aéroportés très volumineux que des spectromètres gamma portatifs.

INTRODUCTION

The Geological Survey of Canada has been involved with the calibration of ground and airborne gamma-ray spectrometers since it constructed the first calibration facility for airborne spectrometers in 1968 (Grasty and Darnley, 1971). Similar calibration facilities have now been constructed in many countries throughout the world.

Calibration facilities for gamma-ray spectrometers are usually four or five large concrete slabs or pads with known concentrations of potassium, uranium, and thorium. They are used to derive the calibration constants for converting the spectrometer count rates in the potassium, uranium, and thorium windows to ground concentrations of potassium, uranium, and thorium.

Recent analysis of the calibration data obtained from the Geological Survey of Canada facilities for airborne gamma-ray spectrometers at Uplands airport, Ottawa, showed that the calibration constants were poorly known because of uncertainties in the radioelement concentrations of the pads (Grasty, 1987). This was also found for the smaller calibration facilities for portable gamma-ray spectrometers at Bell's Corners near Ottawa. There was clearly a requirement to improve the Canadian calibration facilities for both ground and airborne gamma-ray spectrometers.

In the summer of 1988, sets of small transportable pads 1 m x 1 m x 30 cm and weighing approximately 675 kg were constructed specifically for calibrating portable spectrometers. However, due to problems of radon leakage and inhomogeneities in the uranium pads, a new set of uranium pads was constructed in the summer of 1989. This new set, manufactured from a uranium-rich phosphate slag, had none of the problems of the first set which had been manufactured using a high concentration uranium ore.

Calibration experiments with these small pads showed that they could also be used for calibrating large volume aircraft spectrometers, thereby replacing the much larger and more expensive aircraft calibration pads. This paper describes the design and construction of these small transportable pads and shows how they can be used for the calibration of both ground and airborne gamma-ray spectrometers.

DESIGN OF PORTABLE GAMMA-RAY SPECTROMETER CALIBRATION PADS

Dimensions

When using a portable gamma-ray spectrometer for measuring ground concentrations of potassium, uranium, and thorium, the gamma radiation comes from a source which is effectively infinite in depth and horizontal extent. Calibration pads for portable spectrometers are generally 2 to 3 m in diameter and around 50 cm in depth and have not reached their infinite source value. Consequently, a geometric correction factor must be applied when using pads for calibration.

The geometric correction factor depends on a variety of factors such as the depth, diameter, and density of the pads and on the energy of the gamma radiation being considered. The correction factor also depends on the height of the centre of the detector above the pad surface, which is approximately 6 cm for a typical portable gamma-ray spectrometer.

Table 1 and Figure 1 show the effect of varying the diameter of a circular pad on the window count rates of a portable spectrometer, keeping the density and thickness constant (2.25 g/cm^3 and 50 cm respectively). The count rates are compared to the values that would be obtained over an infinite source and were calculated using a computer program developed by Løvborg et al. (1972). The results are shown for gamma radiation at 1.46 MeV from potassium-40 as well as the highest energy gamma radiation at 2.62 MeV from thallium-208 in the thorium decay chain. They show that even with a diameter of 3 m, a geometric correction factor should be applied to the spectrometer sensitivities.

Table 1. Response of a typical portable spectrometer to gamma radiation from 50 cm thick circular pads of different diameter (density = 2.25 g/cm^3, detector elevation 6 cm)

	Percentage of infinite source	
Pad diameter (cm)	Potassium window (1.46 MeV)	Thorium window (2.62 MeV)
50	65.1	60.4
75	78.6	75.4
100	85.2	83.1
125	88.8	87.5
150	91.0	90.1
175	92.5	91.8
200	93.6	93.1
225	94.4	93.9
250	95.0	94.6
275	95.5	95.2
300	95.9	95.6

Almost all calibration pads for portable spectrometers are permanent installations in the ground, generally with their top surface at ground level. A disadvantage of such an installation is that the moisture content of the pads will vary and change the flux of gamma radiation emitted from the pads. Stromswold (1978) has found seasonal variations of 5 percent in the gamma-ray activity of the Unites States calibration facilities at Walker Field, Grand Junction, Colorado, which were attributed to seasonal moisture fluctuations within the pads. This variation in moisture content makes it difficult to assign reliable potassium, uranium, and thorium concentrations to the pads and results in uncertainties in the calibration constants of the spectrometer. In order to overcome the problem of pad moisture fluctuations, consideration was given to the construction of small transportable pads which could be stored indoors and moved outside for calibration.

In selecting the optimum size for transportable pads, there has to be a compromise between the size of the pad and the correction factor that has to be applied to the calculated window sensitivities of the spectrometer to allow for the noninfinite source of the pads. If the pads are too small, the correction factor may be so large that the calibration of the spectrometer becomes unreliable.

For a cylindrical pad of a fixed weight, there is an optimum diameter and thickness that will give the maximum count rate for a particular gamma-ray energy. This is illustrated in Figure 2 for high energy gamma-rays at 2.62 MeV which shows that for a cylinder of 675 kg and density 2.25 g/cm^3 the optimum diameter is approximately 1.2 m.

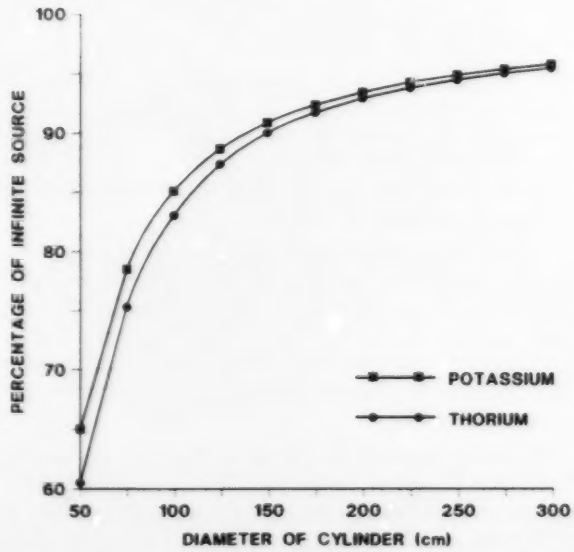

Figure 1. Response of a typical portable gamma-ray spectrometer to gamma radiation from 50 cm thick cylindrical pads of different diameter (density 2.25 g/cm^3, detector elevation 6 cm).

A pad of this size will then give about 85 percent of the infinite source count rate. The response of these optimum cylinders (measured as the percentage of the infinite source response) was calculated as a function of the weight of the cylinders for gamma radiation at 2.62 MeV. The results presented in Figure 3 show that up to about 500 kg, the response increases rapidly with increasing weight. Above about 1000 kg, the response increases much more slowly.

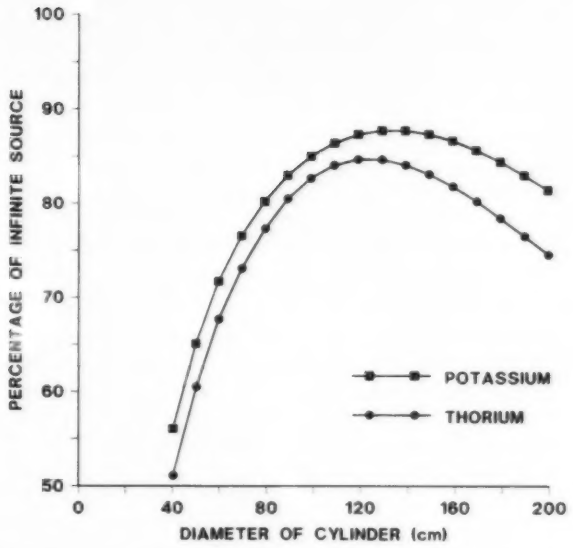

Figure 2. Response of a typical portable gamma-ray spectrometer to gamma radiation from cylindrical pads of different diameter and thickness with a fixed weight of 675 kg (density 2.25 g/cm^3, detector elevation 6 cm).

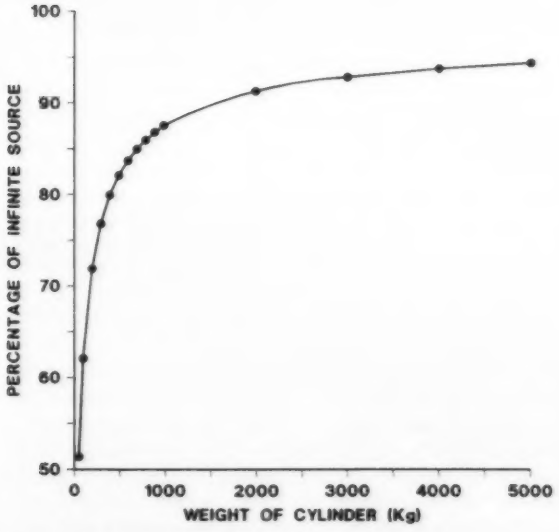

Figure 3. Response of a typical portable gamma-ray spectrometer to 2.62 MeV gamma radiation for optimum cylindrical pads of different weight (density 2.25 g/cm^3, detector elevation 6 cm).

A calibration pad that is 1 m x 1 m x 30 cm and made of typical concrete of density 2.25 g/cm^3 will weigh 675 kg. Such a pad is easy to construct and can easily be lifted by most small pallet trucks or forklifts. A square cross-section pad of side "a" will give the same count rate as a cylindrical pad with a diameter of $\pi a/2^{3/2}$ (Løvborg, 1984). Consequently, a square pad of side 1 m will give the same count rate as a cylindrical pad with a diameter of 111 cm. It was calculated that for 2.62 MeV gamma rays from thorium, such a pad would produce 84.8 percent of the count rate obtained from an infinite source. This is close to the optimum value of 85.3 percent for a cylinder of this weight.

From these considerations, it was decided to construct a set of calibration pads 1 m x 1 m x 30 cm and mount them on a wooden pallet so they would be transportable. Because of their small size, compared to standard portable calibration pads, it was felt that there would be less problem in making them uniform and in accurately determining their radioactive concentrations.

Ideal concentrations

A minimum of four calibration pads with known concentrations of potassium, uranium, and thorium are required to determine the calibration constants of a spectrometer. Ideally, three of these pads should provide pure potassium, uranium, and thorium spectra so that the interfering effects of these elements can best be determined. A fourth low radioactivity pad is required to remove the effects of background radiation from the surrounding ground, the equipment, cosmic radiation, and radon decay products in the air.

An important consideration in selecting the ideal concentrations for the transportable pads is the length of time required to perform the calibration. The pads should be sufficiently radioactive to minimize this calibration time without being so radioactive that spectral distortion occurs and results in incorrect calibration constants. For a standard portable spectrometer with a 7.6 cm x 7.6 cm (3 inch x 3 inch) sodium iodide detector, this distortion will occur when the scintillation rate exceeds about 10 000 scintillations per second. To be on the safe side, the ideal concentrations were selected so that a scintillation rate of 2000 per second was not exceeded.

In the case of potassium, problems of high count rate do not arise with a standard 7.6 cm x 7.6 cm (3 inch x 3 inch) detector. This is because the maximum potassium concentration of a concrete pad that can be achieved in practice is one made from pure potassium feldspar and cement. With such a pad the concentration will be about 8 percent, which will give a scintillation rate of less than 2000 per second. A uranium pad with a concentration of 50 ppm and a thorium pad with 125 ppm will both give approximately 1800 scintillations per second over an infinite source. With this concentration, there will be no danger of spectral distortion occurring. Table 2

Table 2. Ideal pad concentrations (IAEA, 1989)

	K (pct)	eU (ppm)	eTh (ppm)
Blank Pad	0	0	0
K Pad	8	0	0
U Pad	0	50	0
T Pad	0	0	125

shows these ideal concentrations for calibration pads for portable gamma-ray spectrometers. These are the concentrations recommended by the International Atomic Energy Agency (IAEA, 1989).

CONSTRUCTION OF TRANSPORTABLE PADS

Raw materials

The pads were constructed from typical construction concrete containing cement, sand, and coarse aggregate. Suitable aggregate for the background, uranium, and thorium pads can be any low radioactivity material such as crushed limestone, dolomite, or a basic igneous rock. Fortunately, in the Ottawa area, there are many limestone quarries that provide the aggregates for most of the concrete manufacturing plants. Sand from local gravel pits that consists primarily of quartz is commonly used as the fine aggregate and is also low in radioactivity.

The most important criterion in selecting the thorium ore for the thorium pad is the thorium-to-uranium ratio. To achieve an optimum pad, this ratio should be as high as possible. The particular ore used in the thorium pad, a rare earth phosphate called britholite with a thorium concentration of approximately 2.5 percent, was obtained from Oka, Quebec near Montreal (Gold and Vallée, 1969). The thorium/uranium ratio of 130 is much higher than can be obtained for monazite sand, which is commonly used in pad construction. The ore (OKA-2) was used by the Canada Centre for Mineral and Energy Technology (CANMET) in the preparation of a laboratory thorium gamma-ray counting standard RGTH-1 for the IAEA (Smith et al., 1986a). OKA-2 has also been analyzed for its uranium and thorium content by 29 international laboratories (Smith et al., 1986b).

A source of potassium for the potassium pad was not expected to present a difficult raw materials problem since potassium feldspar is available as a commercial product in most countries with a ceramics industry. However, in Canada most of the potassium feldspar originates from the United States and is in a powder form that is unsuitable for pad construction. In addition, it is obtained from crushed granite which frequently contains significant concentrations of uranium and thorium.

In the Ottawa area there are many old feldspar quarries that ceased operation around the 1950s. Several of these still have large dumps. However, because most of the feldspar is associated with pegmatites, it frequently contains undesirable concentrations of uranium and thorium. A source of suitable feldspar was finally located near Perth, Ontario (Sabina, 1987), after visits had been made and samples analyzed from a large number of old quarries. Approximately 5000 kg of feldspar, sufficient for constructing several transportable pads, were collected. All the material was hand picked to make sure that the potassium concentration would be as high as possible and to minimize contamination with uranium and thorium.

In selecting suitable uranium material for the uranium pad, it is important that it has a low emanation power. This is the fraction of the total radon produced by radioactive decay that escapes from the material. It is also desirable to use a source of uranium that has a low concentration of thorium.

A Canadian uranium reference ore designated BL-5, available from CANMET (Faye et al., 1971) appeared ideal for the uranium pad. The material is a low-grade uraninite from Beaverlodge, Saskatchewan and was used in the preparation of the International Atomic Energy Agency uranium laboratory gamma-ray counting standard RGU-1 (IAEA, 1987). BL-5 was used for the uranium pads in the Canadian aircraft and portable spectrometer calibration facilities and in aircraft pads in Thailand (Grasty, 1987). It has been extensively studied and has been shown to lose less than 2 percent of its radon in a dry state (Grasty and Dyck, 1984). Besides being a low emanator of radon, it also has the advantage of being in radioactive equilibrium and unlike many uranium ores has negligible thorium.

In the summer of 1988, eight uranium pads (the minimum load required by the concrete plant) were manufactured using this particular uranium ore. However serious problems of radon leakage and inhomogeneity of the pads were encountered.

In order to test the homogeneity of the uranium pads constructed with the uranium ore BL-5, total count measurements were made on their surface using a 7.6 cm x 7.6 cm (3 inch x 3 inch) lead-shielded portable gamma-ray spectrometer. Nine measurements of two minutes were made on each pad on a 25 cm square grid. Table 3 gives a summary of these total count measurements as well as the laboratory analyses of samples taken during the pouring of the pads. The values shown are the mean and one standard deviation.

It is clear from the laboratory analyses that the first two uranium pads that were poured (U1 and U2) have a significantly higher uranium concentration than the remaining pads. The total count portable spectrometer measurements confirm this variation but also suggest that there is a progressive decrease in activity of the concrete during the entire pouring of the pads. Apparently, the mixing of the concrete and uranium grains in the cement truck results in a partial separation of the more dense uranium ore particles. Because of this variation in the uranium concentration, there is a problem in assigning accurate analyses to the first two pads.

The homogeneity measurements using the lead-shielded portable spectrometer were carried out 11 days after the pads were poured. Approximately ten weeks later, the measurements were repeated and showed that the uranium pads had all lost from 9 to 15 percent of their gamma-ray activity (Table 4). Apparently, the alkalis in the cement had broken down the uranium grains allowing a partial loss of radon to occur. This was a somewhat surprising result considering that the uranium ore BL-5 had been especially selected because it was a low emanator of radon. However, the loss of radon from uranium pads has been observed in Thailand (Grasty, 1987), the United States (Stromswold, 1978), and Denmark (Løvborg et al., 1978) and is now being recognized as a common problem in the construction of calibration pads.

In an attempt to rectify the problem of radon leakage, two different sealers were applied to pads U1 and U2. Pad U1 was sealed with a polyester resin sealer on August 21st and pad U2 was sealed with an acrylic latex water-based sealer on August 25th. Both pads were monitored periodically with the lead-shielded portable spectrometer after they were sealed.

The results of the total count measurements for pad U1, presented in Table 4, clearly show a build-up of gamma-ray activity from the time the sealers were applied. Approximately one week after sealing, the total count rates for both U1 and U2 had increased to values close to those measured soon after the pads were poured. Since radon has a half-life of 3.8 days, the gamma-ray activity due to decay products of radon will take approximately three weeks to reach equilibrium. Both sealers therefore appeared to be capable of preventing a loss of radon. However, after a few months both uranium pads U1 and U2 were again found to be losing their gamma-ray activity. Consequently it was considered necessary to find some more suitable uranium material which would neither lose radon nor mix unevenly in the cement truck.

An industrial plant operating near Montreal produces elemental phosphorus by the electrothermal method. The phosphate ore, which is mined in central Florida, contains about 200 ppm of uranium. Most of the uranium and associated radionuclides are retained in the slag, which is a hard, ceramic-like material composed principally of calcium silicate. Analysis of the slag showed that it was a low emanator of radon and had a low concentration of thorium. These studies also showed that radium-226 and thorium-230 were in radioactive equilibrium with their parent uranium-238. However, the more volatile decay products, lead-210 and polonium-210, are preferentially removed in the electrothermal process and are therefore much below equilibrium. However, this is not a problem in calibrating a gamma-ray spectrometer since polonium-210 is an alpha emitter and lead-210 only produces gamma rays at 46 keV, which is well below any energies of interest.

Electron microprobe studies showed that the uranium in the phosphate slag was not in the form of discrete uranium minerals but dispersed uniformly throughout the material. It was therefore expected that the phosphate slag would be unaffected by the alkaline gels in the concrete. Total count portable gamma-ray spectrometer measurements on a small

Table 3. Laboratory analyses and homogeneity measurements of first set of uranium pads showing variations in their concentrations

Pad	Laboratory analyses		Portable spectrometer measurements	
	eU (ppm)	N	Total counts	N
U1	57.88 ± 2.37	11	15 908 ± 304	9
U2	56.37 ± 1.95	11	14 697 ± 285	9
U3	50.13 ± 1.55	11	14 456 ± 180	9
U4	49.01 ± 1.00	11	14 366 ± 354	9
U5	48.81 ± 1.22	11	14 309 ± 152	9
U6	50.30 ± 0.91	11	14 299 ± 240	9
U7	48.26 ± 0.75	11	13 889 ± 302	9
U8	47.68 ± 1.57	11	13 926 ± 226	9

N = Number of measurements
Errors are at the one sigma level

Table 4. Results of sealing uranium pad U1 with polyester resin

Date (1988)	Total count*
May 28	Pads poured
June 8	16 200 ± 90
Aug 21	14 925 ± 50
Aug 21	Sealed
Aug 22	15 150 ± 71
Aug 23	15 263 ± 71
Aug 25	15 713 ± 72
Aug 26	15 765 ± 63
Aug 27	15 638 ± 63
Aug 29	15 911 ± 63
Aug 30	15 853 ± 63

* The errors indicated are at the one sigma level and were calculated theoretically from the total number of counts accumulated.

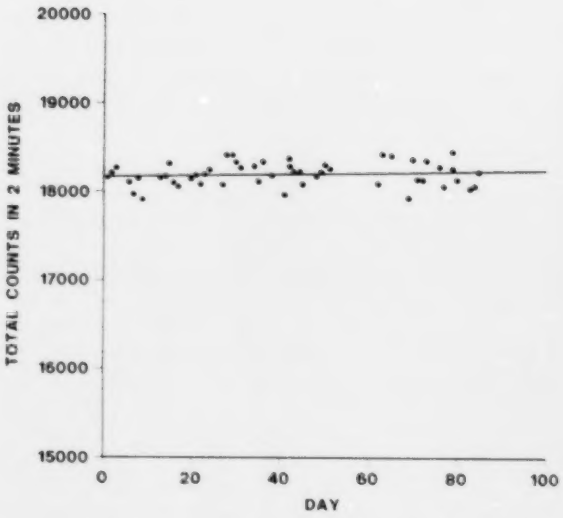

Figure 4. Portable gamma-ray spectrometer total counts from a concrete block manufactured from phosphate slag.

Table 5. Analysis of pad materials

Material	Use	K (pct)	U (ppm)	eTh (ppm)
Limestone	B, U & T Pads	1.3	1.0	1.2
Sand	B, U & T Pads	1.6	0.9	3.3
Cement	All Pads	0.5	2.0	4.0
K-Feldspar	K Pads	10.8	0.3	0.5
Phosphate Slag	U Pads	0.4	210	2.5
Thorium Ore	T Pads	–	200*	27 000
* Based on the published Th/U ratio (Smith et al., 1986b)				

concrete test block manufactured using the phosphate slag showed that there was negligible radon loss over a three-month period (Fig. 4). The small increase in gamma-ray activity over the initial measurement period is believed to be due to a loss of moisture from the concrete block. Measurements one year later confirmed that there is no radon loss from pads constructed in this way. This particular material therefore appeared to solve the problem of radon loss from uranium pads and was therefore acquired for the construction of the uranium pads.

Table 5 gives the analyses of the materials used in the construction of the blank, potassium, and thorium pads in 1988 and of the second set of uranium pads constructed in 1989. The analyses were performed in the gamma-ray laboratory of the Geological Survey of Canada using the new IAEA counting standards (Grasty et al., 1982).

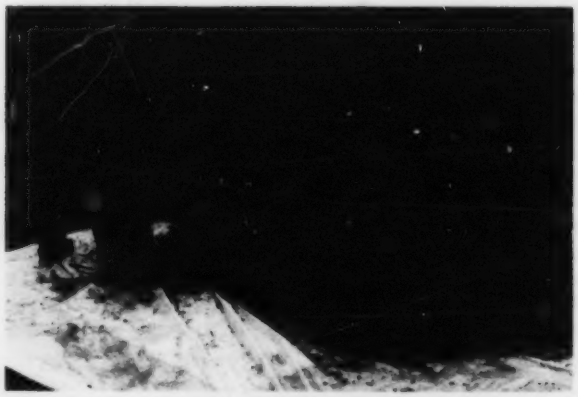

Figure 5. The feldspar after crushing to pass a 20 mm sieve. GSC 1991-122

Because of the difficulty of measuring low concentrations of uranium in the thorium ore, the uranium value is based on its published uranium-to-thorium ratio (Smith at al., 1986b).

Preparation of materials

In constructing the thorium and uranium pads by mixing uranium- and thorium-rich material with a typical concrete mix, it is undesirable to use a coarse aggregate with a large maximum size. This is because of problems in sampling and analyzing the concrete. When a fixed volume of concrete is taken for analysis, the amount of sand and cement in the sample will show more variation when a larger aggregate is used. Since the uranium and thorium materials occupy the spaces between the aggregate, this means that the quantity of uranium and thorium in the sample will also show more variation. For this reason the maximum size of the coarse aggregate should be kept as small as possible. The minimum size of the limestone aggregate that could be used to give a good strength concrete was 10 mm. This was the size used for the uranium, thorium, and blank pads.

In making a good concrete from the potassium feldspar, it was necessary to crush the material into both a fine and coarse aggregate. The fine aggregate would then fill in the spaces between the coarse material and produce a workable, high density, low porosity concrete.

The feldspar was first crushed to pass a 20 mm sieve (Fig. 5). This crushing produced both fine and coarse aggregate. However, based on previous experience in using feldspar for pad construction, it was judged that more fine aggregate was required. Approximately one third of the original crushed feldspar was further crushed to pass a 5 mm sieve. The resultant feldspar then showed a variation in size from 20 mm downward. This larger size aggregate compared to the 10 mm limestone aggregate for the uranium and thorium pads was not expected to cause a sampling problem because both the fine and coarse aggregate were made of the same material.

Figure 6. The metal forms used for pad construction. GSC 1991-124

Figure 7. Phosphate slag being loaded into the cement truck. GSC 1991-130

Available information on calibration pads constructed in various parts of the world shows that a major problem that limits their effective use relates to the difficulties of establishing reliable estimates of their concentrations. This problem arises because of a large variation in the analyses of the concrete samples taken during pad construction, due to difficulties of taking a representative sample. The radioactive concentration of a concrete containing a small amount of crushed high activity ore cannot be estimated reliably unless a sufficient number of ore particles are included in each sample taken for analyses. To minimize these sampling problems, careful consideration was given to the grain size of the thorium ore used in the pads.

In order to achieve a statistical error of one percent in the analyses of the thorium pads, there should be at least 10 000 ore particles in each sample of concrete analyzed. To assure this number of particles, the grain size should be chosen depending on the original concentration of the ore, the final concentration of the pad, and the weight of the samples taken for analysis.

The thorium ore was crushed and sieved to a variety of grain sizes and the average weight of particles within a particular grain size was measured. From these average weights, it was calculated that provided the thorium ore was crushed to pass a 1 mm sieve, there would be only minor variations in the laboratory analyses of the concrete. The thorium ore was therefore crushed to pass through a 20 mesh sieve. The minus 100 mesh fraction was discarded so that the thorium ore and the sand had a similar grain size distribution and would therefore mix well.

The uranium-rich slag for the uranium pads was available in several different sizes. To be compatible with the grain size of the sand and limestone aggregate, the phosphate slag was selected to pass a 5 mm sieve. Since the silicate has a relatively low uranium concentration of 210 ppm (Table 5), a large quantity is required to produce the recommended uranium concentration of 50 ppm (Table 2). Sampling problems in the analysis of the final concrete mix were therefore unlikely.

Based on the density of typical concrete, enough feldspar, phosphate slag, and thorium ore were prepared for eight sets of calibration pads. Because of the small amount of thorium ore that had to be mixed with a large quantity of concrete, an initial dilution of the thorium ore was carried out. The required amount of thorium ore for eight pads was blended for one hour with approximately 125 kg of the sand that was to be used in the construction. This blended material was stored in 4 five gallon pails that could easily be loaded into the cement truck. The phosphate slag was stored in approximately 50 five gallon pails and the crushed feldspar stored in approximately 160 five gallon pails.

Construction procedures

The transportable pads were made by pouring the concrete from a cement truck into metal forms mounted on wooden pallets (Fig. 6). The concrete manufacturing plant that was used for the blank, uranium, and thorium pads was located about 40 minutes drive from the construction site. The thorium concentrate was added to the cement truck at the concrete plant. As well as the 40 minutes slow blending time en route to the construction site, there was an additional 10 minutes of fast blending at the site before the thorium pads were poured.

The uranium pads were manufactured using the same concrete matrix used for the thorium pads. However, because of the large amount of phosphate slag required, it was necessary to reduce the amount of sand and limestone aggregate in the concrete mix. A grain size analysis of the phosphate slag showed there were approximately equal proportions of sand-size particles and coarse aggregate. The quantities of sand and limestone aggregate added to the cement truck were therefore both reduced by the same amount, the total reduction being equal to the required weight of phosphate slag. The phosphate

slag was added to the cement truck at the construction site (Fig. 7) and the entire mixture of cement, sand, limestone aggregate, and phosphate slag was then blended for 15 minutes before the uranium pads were poured.

The potassium pads required a different operational procedure because all the materials were loaded by hand. Another manufacturing plant was selected where the materials could be loaded from a gangway, directly into the cement truck below (Fig. 8). The cement was measured into five gallon pails to give a feldspar to cement ratio of 4:1.

It was intended to manufacture eight sets of pads. However, there was only enough concrete to complete seven thorium and seven potassium pads. The shortage of concrete for the thorium pads was due to an error at the concrete manufacturing plant. In the case of the potassium pads, the amount of material had been based on the significantly lower density of potassium pads that had been previously constructed.

PAD CONCENTRATIONS

Sampling and analyses

In order to use the pads for the calibration of gamma-ray spectrometers, it is essential that the radioactive concentrations of the pads be known at the time of calibration. These concentrations are normally obtained from laboratory gamma-ray measurements of concrete samples taken when the pads are poured. However, for permanent calibration facilities, the in-situ concentrations of the pads will vary due to changes in their moisture content. Consequently, it has always been difficult to decide whether the analyses should be performed on oven-dried samples, wet samples, or samples that have dried naturally.

With transportable pads, problems related to their moisture content can be avoided. This is because the pads can be left to dry naturally and changes in their moisture content minimized either by covering the pads or by keeping them indoors. Therefore all samples taken for analyses were left to dry naturally.

Figure 8. Feldspar being loaded into the cement truck. GSC 1991-128

The Geological Survey of Canada (GSC) laboratory gamma-ray spectrometer analyzes samples in metal cans 10 cm in diameter by 3 cm deep (Grasty et al., 1982). For convenience, the concrete samples analyzed were poured into cardboard cylinders with the same inside diameter as the laboratory sample cans (Fig. 9). One cardboard cylinder of wet concrete mix was collected for every pad poured. Within a few days of the pads being poured, the concrete cylinders were cut into slices and left to dry until their weights remained constant. Each cylinder produced from 9 to 11 samples for the analysis of each pad. The samples were also used to measure the density of the pads.

The GSC gamma-ray laboratory utilizes two 14 cm x 14 cm (5 inch x 5 inch) sodium iodide detectors. Counts are recorded in the standard three energy windows covering 1.46 Mev gamma rays from potassium-40, 1.76 MeV gamma rays from bismuth-214 in the uranium decay chain, and 2.62 MeV gamma rays from thallium-208 in the thorium decay series. Calibration of the spectrometer was performed using the new IAEA potassium, uranium and thorium standards RGK-1, RGU-1, and RGTh-1 (IAEA, 1987) respectively. Each sample was measured for 20 minutes and the three standards and a nonradioactive background sample of distilled water measured after approximately every 20 samples.

Homogeneity tests and grade assignments

In calibrating a spectrometer on the pads, it is important that the concrete is homogeneous and the laboratory analyses therefore represent the volume of material viewed by the

Figure 9. Concrete samples being taken for later analysis. GSC 1991-129

spectrometer. With large pads this can be done by taking portable spectrometer measurements at different places on the pad surface. However, with small transportable pads, the count rates will vary with the position of the detector even when the pads are homogeneous. Near the edge of the pads the counts will be reduced because of the reduced volume sampled by the spectrometer.

In order to verify that the potassium, uranium, and thorium pads were homogeneous, measurements were made on their surface using a lead-shielded portable spectrometer with a 7.6 cm x 7.6 cm (3 inch x 3 inch) sodium iodide detector. The lead shield was an annular ring 5 cm thick and 15 cm high which fitted around the detector housing and restricted the field of view of the detector (Fig. 10). Nine measurements of two minutes were made on a 25 cm square grid on each pad. Counts were recorded in the three standard radioelement windows as well as the total count window. The total count results were used to assess the homogeneity of the concrete because of its greater statistical accuracy compared to the window measurements.

Table 6 gives a summary of the total count homogeneity measurements on the potassium, uranium, and thorium pads. The values shown are the mean and one standard deviation.

In assessing the homogeneity of each pad, it is necessary to take into account the theoretical variation of the total count due to Poisson counting statistics. Even when the pad is completely homogeneous, the total count cannot be expected to have the same value for all nine measurements on each pad. The expected spread in the total count will be given by the square root of the total number of counts recorded. As an example, if the true total number of counts on the potassium pads is 6400, the expected spread of the measurements will be $6400^{1/2} = 80$ counts.

Table 6 shows that the total count variations of the potassium pads are generally about 1.5 percent and all are less than 2.5 percent. This is comparable to the one sigma theoretical spread of 1.2 percent. By analyzing the total count measurements on all the potassium pads, any real variations in their concentrations can be estimated (Glynn and Grasty, in press). Using their technique, it was calculated that at the 95 percent confidence level, any real variations in the potassium concentration of the potassium pad were less than 1.7 percent. Similarly, real variations of less than 1.5 percent and 2.6 percent were found for the uranium and thorium pads, respectively.

These total count homogeneity measurements were carried out with a lead-shielded portable spectrometer which samples a much smaller volume of material than one that is unshielded. Any real variations in the volume of concrete sampled when calibrating with an unshielded spectrometer would be expected to be significantly lower than the variations calculated for the shielded detector with its reduced sample volume. We have therefore concluded that any variations in the homogeneity of the pads are small and that the average of all the laboratory gamma-ray measurements will give the best estimate of the pad concentrations.

Table 7 gives the mean concentrations of the laboratory analyses for the four sets of pads, together with the number of samples analyzed. The errors indicated are the one sigma spread of the individual analyses and do not take into account any uncertainties resulting from the calibration of the laboratory spectrometer or in the concentrations of the standards. By routinely monitoring the counts recorded from the three IAEA standards, errors in the calibration of the laboratory spectrometer were estimated to be approximately 0.5 percent for potassium and uranium and 1.2 percent for thorium. These errors include uncertainties in the concentration of the standards (IAEA, 1987).

The error in the mean concentration of N measurements with a standard deviation of σ is given by $\sigma/N^{1/2}$. The combined error, E, in the mean concentration of the pads was then calculated using the formula:

$$E^2 = \sigma^2/N + (CP/100)^2$$

Figure 10. Homogeneity tests with lead-shielded spectrometer. GSC 1991-127

Table 6. Portable spectrometer total count homogeneity measurements

	K — pads	U — pads	T — pads
K1	6 481 ± 107	U1 14 036 ± 291	T1 15 118 ± 335
K2	6 477 ± 114	U2 13 940 ± 229	T2 15 389 ± 324
K3	6 542 ± 165	U3 14 003 ± 115	T3 15 212 ± 446
K4	6 551 ± 95	U4 14 121 ± 198	T4 15 350 ± 498
K5	6 619 ± 83	U5 13 900 ± 181	T5 Not measured
K6	6 567 ± 87	U6 14 017 ± 262	T6 15 350 ± 270
K7	6 460 ± 117	U7 13 918 ± 206	T7 15 379 ± 362
		U8 13 844 ± 106	

Table 7. Analyses of mini-pad concrete samples

Pads	K (pct)	eU (ppm)	eTh (ppm)	N
B-Pads	1.43 ± 0.05	0.94 ± 0.17	2.32 ± 0.49	84
K-Pads	7.57 ± 0.33	1.22 ± 0.73	1.40 ± 0.98	71
U-Pads	1.07 ± 0.07	46.93 ± 1.92	2.75 ± 0.60	80
T-Pads	1.38 ± 0.14	1.74 ± 1.48	121.6 ± 7.35	88

N = Number of samples analyzed.
Errors indicated are at the one sigma level.

where P is the calibration error in percent and C is the mean concentration of all N samples.

The thorium pads were made by adding a small amount of thorium ore to the same limestone and sand matrix as the blank pad. Consequently, the potassium concentrations of the thorium pads should be the same as the blank pad. However, the results in Table 7 show that they have slightly different values. This is believed to be due to the difficulty of correcting for the relatively large contribution of scattered thorium gamma rays in the potassium window. We have therefore assumed that the potassium analyses of the blank pad are the best estimates of the potassium concentrations of the thorium pads. The concentrations assigned to the pads are given in Table 8. The densities of the pads, also shown, were determined from measurement on a representative suite of samples from each set of pads.

CALIBRATION OF PORTABLE SPECTROMETERS — THEORY

The conversion equations for a portable spectrometer

There are two techniques that can be employed in converting the count rates in the three radioelement windows of a portable gamma-ray spectrometer to concentrations of K, U, and Th in the ground. The two techniques are the standard stripping procedure and the more general matrix inversion method.

In the standard stripping procedure, two basic sets of calibration constants are required. They are:

1. the three window sensitivities, and
2. the stripping ratios.

The three window sensitivities are normally expressed as:

a) counts per second in the potassium window per percent potassium,

b) counts per second in the uranium window per ppm uranium, and

c) counts per second in the thorium window per ppm thorium.

Table 8. Assigned pad concentrations

Pads	K (pct)	eU (ppm)	eTh (ppm)	Density (g/cm³)
B - Pads	1.43 ± 0.01	0.94 ± 0.02	2.32 ± 0.06	2.28
K - Pads	7.57 ± 0.05	1.22 ± 0.09	1.40 ± 0.12	2.23
U - Pads	1.07 ± 0.01	46.93 ± 0.32	2.75 ± 0.07	2.24
T - Pads	1.43 ± 0.02	1.74 ± 0.16	121.6 ± 1.66	2.28

The errors quoted take into consideration the number of samples analyzed. They also include uncertainties in the calibration of the laboratory spectrometer and in the concentrations of the IAEA standards. It is assumed that the analyses for the blank pad are the best estimates of the concrete matrix of the thorium pad.

Due to Compton scattering in the ground, some counts from 2.62 MeV thallium-208 photons from a pure thorium source are recorded in the lower energy potassium and uranium windows. Counts in the lower energy windows also arise from the incomplete absorption of 2.62 MeV photons in the detector or from other lower energy gamma-ray photons in the thorium decay series. Similarly, counts will be recorded in the lower energy potassium window from a pure uranium source and can also appear in the high energy thorium window due to high energy gamma-ray photons of bismuth-214 in the uranium decay series. The stripping ratios are the ratios of the counts detected in one window to those in another window from pure sources of potassium, uranium, and thorium. For convenience, the notation has been adopted in which , α, β, and γ are the ratios of the counts in a lower energy window to those in a higher energy window and a, b, and g are the reversed stripping ratios, the ratio of the counts detected in a high energy window to those detected in a low energy window.

α is the thorium into uranium stripping ratio, equal to the ratio of the counts detected in the uranium window to those detected in the thorium window from a pure thorium source.

a is the reversed stripping ratio, uranium into thorium, equal to the ratio of counts detected in the thorium window to those detected in the uranium window from a pure source of uranium.

Similarly,

β is the thorium into potassium stripping ratio for a pure thorium source,

b is the reversed stripping ratio, potassium into thorium for a pure potassium source,

γ is the uranium into potassium stripping ratio for a pure uranium source and,

g is the reversed stripping ratio, potassium into uranium for a pure potassium source.

Both the stripping ratios and window sensitivities can be determined from measurements on the transportable calibration pads.

Before the count rates can be converted to concentrations, the background count rates in each window must first be removed. This background originates from cosmic radiation, the radioactivity of the equipment, and radioactivity arising from decay products of radon in the air. This background is normally measured by taking the spectrometer in a boat onto a lake or river. A lake or river that is 100 m wide will normally reduce the radiation from the surrounding ground to a negligible level. This background should be monitored periodically to determine how frequently the background should be determined. In some countries, significant changes occur over a few hours in the early morning, due to variations in the concentration of decay products of radon in the air.

The three background corrected window count rates, n_K, n_U, and n_{Th} are sums of the individual count rates from K, U, and Th. Consequently,

$$n_K = n_{K,K} + n_{K,U} + n_{K,Th} \quad (1)$$

$$n_U = n_{U,K} + n_{U,U} + n_{U,Th} \quad (2)$$

$$n_{Th} = n_{Th,K} + n_{Th,U} + n_{Th,Th} \quad (3)$$

where $n_{i,j}$ is the count rate of window i due to element j - i.e. $n_{K,U}$ is the count rate in the potassium window due to uranium.

Using the six stripping ratios, these three equations can be converted to a set of equations relating the three background corrected count rates to the counts in the thorium, uranium, and potassium windows that originate solely from Th, U, and K ($n_{Th,Th}$, $n_{U,U}$, and $n_{K,K}$) :

$$n_K = n_{K,K} + \gamma\, n_{U,U} + \beta\, n_{Th,Th} \quad (4)$$

$$n_U = g\, n_{K,K} + n_{U,U} + \alpha\, n_{Th,Th} \quad (5)$$

$$n_{Th} = b\, n_{K,K} + a\, n_{U,U} + n_{Th,Th} \quad (6)$$

For a portable gamma-ray spectrometer using the conventional window limits, potassium does not produce any counts in the high energy uranium and thorium windows and consequently b and g both have a value of zero. In addition, the value of a is small and for most geological situations can be neglected.

In the case where a, b, and g are zero, equations (4), (5), and (6) are considerably simplified and reduce to the standard stripping equations for the counts in the thorium, uranium, and potassium windows ($n_{Th,Th}$, $n_{U,U}$, and $n_{K,K}$) due solely to Th, U, and K:

$$n_{K,K} = n_K - \beta\, n_{Th} - \gamma\,(n_U - \alpha\, n_{Th}) \quad (7)$$

$$n_{U,U} = n_U - \alpha\, n_{Th} \quad (8)$$

$$n_{Th,Th} = n_{Th} \quad (9)$$

The thorium, uranium, and potassium ground concentrations (c_K, c_U, and c_{Th}) are therefore given by:

$$c_K = (n_K - \beta\, n_{Th} - \gamma\,(n_U - \alpha\, n_{Th})) / s_K \quad (10)$$

$$c_U = (n_U - \alpha\, n_{Th}) / s_U \quad (11)$$

$$c_{Th} = n_{Th} / s_{Th} \quad (12)$$

where s_K, s_U, and s_{Th} are the three window sensitivities defined previously.

These stripping equations assume that a uranium source will have no contribution to the thorium window and also that a potassium source will have no contribution to either the uranium or thorium windows. In most geological situations, the assumption that the value of a is zero produces negligible errors. However, for rocks with high uranium-to-thorium ratios, considerable errors can arise in the estimation of thorium concentration. In addition some portable spectrometers include a gamma-ray peak at 1.12 Mev from bismuth-214 in the uranium decay series for the measurement of uranium. With this gamma-ray peak, there is a significant contribution of potassium to the uranium window and the value of g is no longer zero.

In order to allow for these multiple window interference effects, it is necessary to have a general solution to convert the window count rates to ground concentrations.

The window count rate, $n_{i,j}$ due to a particular element j, is the product of the concentration of that element in the ground and a sensitivity factor for that element in the window being considered. If $s_{i,j}$ is the sensitivity of element j in window i, expressed as count rate per unit concentration (cs^{-1} per unit concentration), then

$$n_{i,j} = s_{i,j}\, c_j \quad (13)$$

where c_j is the concentration of radioelement j in the ground.

Equations (1), (2), and (3) can be written in the form

$$n_i = \Sigma\, s_{i,j}\, c_j \; (i = 1, 2, 3) \quad (14)$$

In matrix notation, equation (14) can be written as

$$N = SC \quad (15)$$

where $N = [n_i]$ is a column vector of background corrected count rates, $S = [s_{i,j}]$ is a 3 x 3 matrix of sensitivities, and $C = [c_j]$ is a column vector of concentrations.

The nine sensitivity constants $[s_{i,j}]$ are normally determined from measurements on calibration pads. The ground concentrations C, can then be determined from the measured window count rates, N, using the equation:

$$C = S^{-1} N \quad (16)$$

where S^{-1} is the inverse matrix of S.

In terms of the more conventional stripping procedure, the sensitivities $s_{1,1}$, $s_{2,2}$, and $s_{3,3}$ are the potassium, uranium, and thorium sensitivities equivalent to s_K, s_U, and s_{Th} in equations (10), (11), and (12).

The stripping ratios ,α , β, and γ are given by:

$$\alpha = s_{U,Th} / s_{Th,Th} \quad (17)$$

$$\beta = s_{K,Th} / s_{Th,Th} \quad (18)$$

$$\gamma = s_{K,U} / s_{U,U} \quad (19)$$

and the reversed stripping ratio a, b, and g are given by:

$$a = s_{Th,U} / s_{U,U} \quad (20)$$

$$b = s_{Th,K} / s_{K,K} \quad (21)$$

$$g = s_{U,K} / s_{K,K} \quad (22)$$

Geometry correction

The transportable pads give somewhat lower count rates than sources that are effectively infinite in size. Consequently, a geometric correction must be applied to the three window sensitivities derived using the pads.

This geometric correction factor depends on the height of the detector above the pad surface. It also depends on the dimensions of the pads, their density, and on the linear attenuation of gamma radiation in the concrete pads. Based on the density of the pads (Table 8) and on the mass attenuation coefficient of gamma rays in concrete (Løvborg, 1984), the linear attenuation coefficient of gamma rays in the concrete pads can be determined for the three energy windows. These results are presented in Table 9.

As shown previously from the work of Løvborg (1984) a square pad of side 100 cm will give the same count rate as a cylindrical pad with a diameter of 111 cm. Using the computer program of Løvborg et al. (1972) for cylindrical detectors, geometric correction factors were calculated for the calibration pads as a function of the detector elevation above the pad surface. These results are shown in Figure 11 for potassium, uranium, and thorium gamma radiation.

The Geometrics/Exploranium GR-410 portable spectrometer has a 7.6 cm x 7.6 cm (3 inch x 3 inch) detector with approximately 1.9 cm (3/4 inch) of insulation between the detector and the bottom of the detector housing. The centre of the detector is therefore 5.7 cm from the pad surface during calibration. The older Geometrics/Exploranium DISA 400 and 400A with a 7.6 cm x 7.6 cm (3 inch x 3 inch) detector and the new Exploranium 256 channel portable spectrometer all have the same sensor configuration as the GR-410. Another common portable gamma-ray spectrometer is the Scintrex Gad-6 which utilizes a prismatic detector (2.5 inches x 2.5 inches in cross-section and 3.5 inches high). This sensor also has approximately 1.9 cm (3/4 inch) of insulation between the detector and its housing. The centre of this detector is therefore 6.3 cm from the pad surface during calibration.

Table 9. Parameters used to calculate percentage of infinite source

Pad	Density (g/cm^3)	Principal energy (MeV)	Mass attenuation coefficient (cm^2/g)	Linear attenuation coefficient (cm^{-1})
K-Pad	2.23	1.46	0.0530	0.1182
U-Pad	2.24	1.76	0.0482	0.1080
T-Pad	2.28	2.62	0.0396	0.0903

In utilizing the transportable pads for calibration, it is convenient to assume that these common gamma-ray spectrometers have detectors that are all 6 cm from the pad surface during calibration. If this common detector elevation of 6 cm is assumed, the geometric correction factors were calculated to differ by less than one percent from the values using the correct detector elevations of 5.7 and 6.3 cm. We have therefore adopted 6 cm as being the common detector elevation above the pad surface. Geometric correction factors for this elevation of 6 cm are presented in Table 10 for potassium gamma radiation at 1.46 MeV in the potassium pads, uranium gamma radiation at 1.76 MeV in the uranium pads, and thorium gamma radiation at 2.62 MeV in the thorium pads.

In some instances the location of the centre of the detector may not be known. In this case the centre of the detector can be determined simply and reliably by moving a small source along the sensor housing and monitoring the total count.

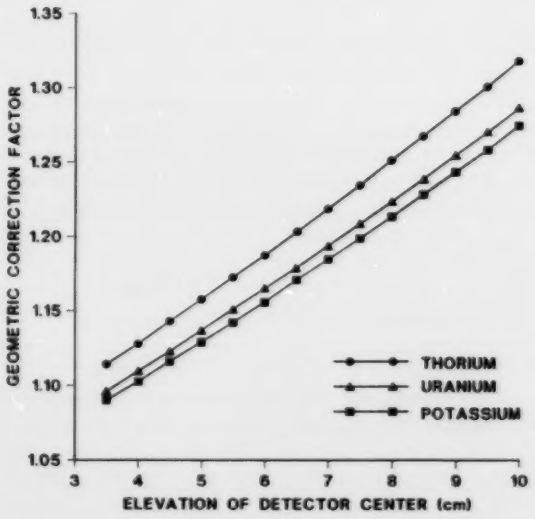

Figure 11. Variation of geometric correction factors with detector elevation for the transportable pads.

Table 10. Percentage of infinite source and geometric correction factors for transportable pads*

Radioelement	Principal energy (MeV)	Percentage of infinite source	Geometric correction factor
Potassium	1.46	86.47	1.156
Uranium	1.76	85.84	1.165
Thorium	2.62	84.17	1.188

* The pads are 1 m x 1 m x 30 cm with the densities shown in Table 8. It is assumed that the centre of the detector is 6 cm above the surface of the pad.

The maximum count rate will be obtained when the source is aligned with the centre of the detector. The appropriate geometric correction factors can then be obtained from Figure 11 which can also be used if the detector elevation is significantly different from the value of 6 cm assumed in Table 10.

Calibration equations

From measurements on any of the four transportable calibration pads, the potassium, uranium, and thorium window count rates n_K, n_U, and n_{Th} are linearly related to the potassium, uranium, and thorium concentrations of the pad, c_K, c_U, and c_{Th}. The equations are:

$$n_K = s_{K,K}\, c_K + s_{K,U}\, c_U + s_{K,Th}\, c_{Th} + b_K \quad (23)$$

$$n_U = s_{U,K}\, c_K + s_{U,U}\, c_U + s_{U,Th}\, c_{Th} + b_U \quad (24)$$

$$n_{Th} = s_{Th,K}\, c_K + s_{Th,U}\, c_U + s_{Th,Th}\, c_{Th} + b_{Th} \quad (25)$$

Here, b_K,b_U, and b_{th} are the background count rates originating mainly from the radioactivity of the surrounding ground but also include a small contribution from the radioactivity of the equipment, cosmic radiation, and the radioactivity of the air. The $s_{i,j}$s are nine sensitivity constants that have to be determined, and give the count rate in window i per unit concentration of element j. These sensitivity constants are for a source with the same geometry as the small pads. The potassium, uranium, and thorium window sensitivities are given by the constants $s_{K,K}$, $s_{U,U}$, and $s_{Th,Th}$ and the six stripping ratios are related to the various $s_{i,j}$s by equations (17) to (22).

Each of the equations (23), (24), and (25) has four unknowns, the three window sensitivities for potassium, uranium, and thorium plus the background. Consequently, from measurements on all four calibration pads the four unknowns can be uniquely determined.

The four sets of equations corresponding to each of the equations (23), (24), and (25) can be reduced to a set of three equations with three unknowns by subtracting the count rates and concentrations of the blank pad from those of the potassium, uranium, and thorium pads. With this method, the unknown backgrounds, b_K, b_U, and b_{Th} are removed from the computation.

The background corrected count rates on the potassium, uranium, and thorium pads are related to the concentrations of the pads and the spectrometer window sensitivities for small pads by the matrix equation:

(26)

$$\begin{vmatrix} n_{K,K} & n_{K,U} & n_{K,Th} \\ n_{U,K} & n_{U,U} & n_{U,Th} \\ n_{Th,K} & n_{Th,U} & n_{Th,Th} \end{vmatrix} = \begin{vmatrix} S_{K,K} & S_{K,U} & S_{K,Th} \\ S_{U,K} & S_{U,U} & S_{U,Th} \\ S_{Th,K} & S_{Th,U} & S_{Th,Th} \end{vmatrix} \times \begin{vmatrix} C_{K,K} & C_{K,U} & C_{K,Th} \\ C_{U,K} & C_{U,U} & C_{U,Th} \\ C_{Th,K} & C_{Th,U} & C_{Th,Th} \end{vmatrix}$$

where $n_{i,j}$ is the 3 x 3 matrix representing the count rate in window i on pad j minus the count rate in window i on the blank pad. Similarly, $C_{i,j}$ is a 3 x 3 matrix representing the concentration of element i on pad j minus the concentration of element i on the blank pad.

In matrix notation

$$N = SC \quad (27)$$

from which the 3 x 3 sensitivity matrix S (for small pads) containing the nine $S_{i,j}$s in equations (29), (30), and (31) may be evaluated using

$$S = NC^{-1} \quad (28)$$

The stripping ratios can then be determined from the window sensitivities for portable pads using equations (17) to (22).

In calibrating a spectrometer, it is necessary to determine the window sensitivities for an infinite source. By making use of the geometric correction factors shown in Table 10, the three equations can be expressed in terms of infinite source sensitivities as follows:

$$S_{K,K} = g_K \times s_{K,K} \quad (29)$$

$$S_{U,U} = g_U \times s_{U,U} \quad (30)$$

$$S_{Th,Th} = g_{Th} \times s_{Th,Th} \quad (31)$$

where S and s represent the potassium, uranium, and thorium window sensitivities for infinite sources and small sources respectively. The g factors are the sensitivity correction factors given in Table 10.

CALIBRATION OF PORTABLE SPECTROMETERS — PRACTICE

In this section, the recommended procedures for calibrating a portable spectrometer using the transportable pads are described. The main points to consider are:

1) pad location,

2) counting time, and

3) variations in atmospheric background.

The main requirement in selecting a site for calibration is an area of ground that is flat and relatively homogeneous in its radioactivity. To eliminate any cross-talk between pads, they should be placed at least 3 m apart, centre to centre.

It is important that the background radiation from the area surrounding the pads should be the same for each pad. In fact, because the pads are a good shield to gamma radiation from the ground, only a small fraction of any background radiation will be detected when calibrating. Unless the ground is both variable and high in radioactivity or there are radioactive sources in the field of view of the spectrometer, problems of background variation from the surrounding ground are therefore unlikely. If there is any doubt, the background being detected on each pad can easily be checked by monitoring the three window count rates on the background pad with the background pad placed in the four pad locations.

The concentrations of the pads were determined on dry material. If the pads are left outside, they should be kept covered to prevent changes in their moisture content and associated variations in their gamma-ray flux.

The time spent recording the window count rates on each pad controls the accuracy of the calibration constants. A longer counting time reduces uncertainties in the window count rate which in turn will increase the accuracy of the calibration. For a typical 7.6 cm x 7.6 cm (3 inch x 3 inch) detector, a 10 minute counting time is realistic, providing calibration constants that are sufficiently accurate for all practical purposes. With this counting time, the total number of counts recorded in the potassium window on the potassium pad, the uranium window on the uranium pad, and the thorium window on the thorium pad will have reached approximately 10 000. This will result in uncertainties in the three window sensitivities of approximately one percent. In practice, it is recommended that this 10 minute counting time should be subdivided into smaller counting intervals. The repeatability of the individual measurements will help to verify that the instrument is functioning correctly. Five individual counting periods of two minutes each would be suitable; however, the actual counting period will depend on the particular instrument being used.

Atmospheric background arises from the decay products of radon. Radon is a gas and can diffuse out of the ground. The rate of diffusion will depend on such factors as air pressure, soil moisture, ground cover, and temperature. The decay products of radon that produce the atmospheric gamma-ray activity, principally lead-214 and bismuth-214, are attached to airborne dust particles. During the night, as the air is cooled and mixing of the air is reduced, the dust particles sink closer to the ground, thereby increasing the atmospheric gamma-ray activity at ground level. As the sun comes up in the early morning, the air is heated, increasing the height of the mixing layer and reducing the radioactivity of the air at ground level. During the day, count rate changes in the uranium window of a portable spectrometer equivalent to ground concentrations of several parts per million uranium have been reported in some parts of the world (Grasty, 1987).

In calibrating a spectrometer on the pads, it is essential that the atmospheric background component remains constant on all four pads during the time required to perform the calibration. This can best be done by monitoring the uranium window on the blank pad. In most places, this background variation will be insignificant and have little effect on the calibration constants. However, if significant background changes are found to occur, it may be necessary to monitor the background pad routinely, at the beginning and end of the calibration. If the background has changed significantly, the entire calibration must be repeated.

In Table 11, typical calibration constants are shown for a portable spectrometer with a 7.6 cm x 7.6 cm (3 inch x 3 inch) detector. The values are the nine window sensitivities for infinite sources. The various stripping ratios are calculated from these window sensitivities using equations (17) to (22). It should be noted that for a portable spectrometer using the standard window positions recommended by the International Atomic Energy Agency (IAEA, 1976), no counts are recorded in the uranium and thorium windows from a pure source of potassium. This is a useful check that the windows have been set in the correct position and have not drifted during the course of the calibration.

Table 11. Typical window sensitivities and stripping ratios for a 7.6 cm x 7.6 cm (3 inch x 3 inch) portable spectrometer

Window sensitivity	K window	U window	T window
K Sens. (Counts/min/pct K)	201.0	0	0
U Sens. (Counts/min/ppm eU)	15.3	21.3	0.42
Th Sens. (Counts/min/ppm eTh)	4.27	4.56	7.81
Stripping Ratios	**Calculated Values From Sensitivities**		
α	4.56/7.81 = 0.584		
β	4.27/7.81 = 0.547		
γ	15.3/21.3 = 0.718		
a	0.42/21.3 = 0.020		
b	0/201.0 = 0		
g	0/201.0 = 0		

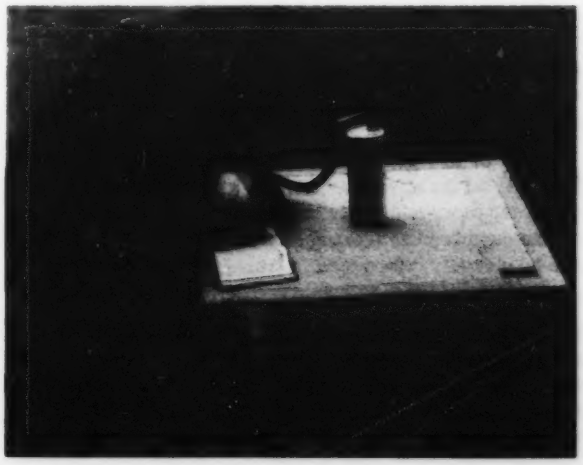

Figure 12. A portable spectrometer being calibrated. GSC 1991-126

Appendix A shows some typical results for a spectrometer calibrated on the transportable pads (Fig. 12) and also shows how the calibration calculations can be performed. In the calculation, the blank pad count rates have been subtracted from the measured count rates on the potassium, uranium, and thorium pads. Similarly, the blank pad concentrations have also been subtracted from the concentrations of the potassium, uranium and thorium pads.

A program for a Hewlett-Packard 15-C calculator that uses a simple matrix method is given in Appendix B for the results reported in Appendix A. The concentrations of the pads used in the example correspond to the pads constructed. A summary of the technical specifications of the pads are

given in Appendix C. Appendix D describes a calibration program for an IBM-PC compatible computer that is available on a floppy disc by contacting the principal author.

COMPARISON OF TRANSPORTABLE AND AIRCRAFT CALIBRATION PADS

Principles of aircraft calibration

In calibrating an airborne gamma-ray spectrometer so that the count rates in the three radioelement windows may be converted to ground concentrations, three basic sets of calibration constants are required (Grasty, 1987). They are:

1) the system stripping ratios,

2) the height attenuation coefficients, and

3) the system sensitivities.

The stripping ratios are used to correct for overlap between the potassium, uranium, and thorium spectra. These stripping ratios are normally determined from measurements on large concrete calibration pads, typically 8 m across and 50 cm thick. These pads could also be used to determine the sensitivities of the spectrometer system. This is not commonly done, however, because of errors introduced both by geometric correction for the noninfinite source represented by the pads, and by extrapolating upward to the normal flying height. Better methods for determining the sensitivities of airborne systems have been devised, using test ranges of known radioelement concentration.

For airborne surveys, the stripping ratios determined at ground level over pads must be corrected for the flying height, because the radioelement spectra are affected by the mass of the air between the aircraft and the ground (Grasty, 1975). The corrected ratios at survey altitude are larger than those at ground level due to the build-up of scattered gamma radiation.

The height attenuation coefficients are used to correct the window count rates for deviations from the planned survey altitude. It has been found by experiment that in the range of altitudes normally encountered in airborne survey operations, the count rate (N) in each window can be adequately represented by a simple exponential expression of the form:

$$N = A \exp(-\mu h) \qquad (32)$$

where A and μ are constants and h is the altitude of the aircraft above the ground. The coefficient μ is found experimentally for each of the three radioelement windows by flying at different altitudes over a test line in an area of uniform radioelement concentration.

The system sensitivities, used to convert the corrected gamma-ray counts to apparent radioelement concentrations, are normally determined from flights over the airborne calibration range, the radioelement concentrations of which are measured on the ground at the time of the calibration flights using a portable gamma-ray spectrometer. The three sensitivities that are determined at the nominal survey altitude are normally expressed as counts per second per unit concentration of each radioelement.

Measurements on Uplands pads

When attempts were made to compare calibration results from the transportable pads with those from the aircraft calibration pads at Uplands airport, Ottawa, a significant problem was encountered. A relatively high uncertainty was found to exist in stripping ratios determined over the Uplands pads. This uncertainty had two causes: the potassium concentration of all five pads has little variation, and there are relatively large uncertainties in the radioelement concentrations of all the pads that had been determined from laboratory measurements on samples drilled from the pads (Grasty and Darnley, 1971).

In an attempt to improve the reliability of the stripping ratio measurements, the concentrations of the five Uplands pads were remeasured using a portable spectrometer calibrated on the transportable pads.

Sixteen measurements of two minutes each were made on a 91 cm (3 foot) square grid on each of the five pads. Tables 12 and 13 show the analyses of the original core samples and the new concentrations measured with the calibrated portable spectrometer respectively. The new concentrations take into consideration uncertainties in the calibration constants of the portable spectrometer as well as errors due to Poisson counting statistics.

Based on uncertainties in the new concentrations, the analyses of the Uplands pads have improved significantly for all three radioelements, particularly for potassium. The slight

Table 12. Original core sample laboratory analyses of Uplands pads

	K(%)	U(ppm)	Th(ppm)
Pad-1	1.70 ± 0.08	2.40 ± 0.24	8.90 ± 0.62
Pad-2	2.27 ± 0.10	7.30 ± 0.15	12.60 ± 0.71
Pad-3	2.21 ± 0.08	3.00 ± 0.3	26.10 ± 0.91
Pad-4	2.21 ± 0.12	2.90 ± 0.304	40.80 ± 1.89
Pad-5	2.33 ± 0.09	11.70 ± 0.35	13.20 ± 0.75

Table 13. Portable spectrometer analyses of Uplands pads

	K(%)	U(ppm)	Th(ppm)
Pad-1	1.656 ± 0.032	3.22 ± 0.11	7.44 ± 0.24
Pad-2	2.161 ± 0.043	8.23 ± 0.18	10.85 ± 0.26
Pad-3	2.073 ± 0.039	4.36 ± 0.22	24.21 ± 0.51
Pad-4	2.079 ± 0.049	4.30 ± 0.28	39.81 ± 0.70
Pad-5	2.210 ± 0.044	12.64 ± 0.27	11.38 ± 0.25

bias in the uranium and thorium analyses is believed to be due to a small error in the background count rate that was used for the uranium and thorium windows of the portable spectrometer. The backgrounds used were not determined on the day the measurements were carried out, but were typical values based on previous experience with the spectrometer. However, this small systematic bias has no effect on the calibration constants derived from measurements on the pads. This is because both the counts recorded on the low background pad and its concentrations are subtracted from the other pads when the calibration data are processed (Grasty, 1987). The bias can therefore be considered as a constant background contribution on all five pads.

Once the best estimates of the concentrations of the five Uplands pads had been made with the portable spectrometer, a calibration was performed to confirm that the new concentrations of the Uplands pads gave improved values of the calibration constants.

The purpose of the calibration pads is to derive the shape of the gamma-ray spectrum of the three radioelements. However, the shape of these spectra may be distorted for a large volume airborne system, if the count rate is high. This distortion arises because of the increased probability at high count rates that two pulses from the detector array will arrive simultaneously at the analyzer, and be processed as a single high energy pulse. Consequently, the observed spectrum appears to have a greater proportion of high energy gamma rays than really exists. The amount of distortion due to these pulse pile-up effects increases with count rate and therefore with detector volume.

The Geological Survey of Canada airborne gamma-ray spectrometer has three separate detector boxes each with four prismatic sodium iodide detectors 10.2 cm x 10.2 cm x 40.6 cm (4 inches x 4 inches x 16 inches). These boxes are designated Box 1, 2, and 3. Because of the large detector volume and its associated high count rate, each of the three boxes was calibrated separately whether the calibration was performed using the Uplands pads or with the transportable pads.

Figure 13. Calibration of one detector package. GSC 1991-125

In the calibration procedure using the Uplands pads, the airborne system was mounted in the Skyvan in its normal flying configuration with each detector box centred on the pads (Fig. 13). A total of approximately five minutes of accumulated one second spectra were recorded on each pad, for each of the three detector boxes. With this length of time any errors due to Poisson counting statistics were found to be negligible. The average spectra recorded on each pad were then used to establish the channel position of the prominent thorium and potassium windows from which the relationship between channel position and gamma-ray energy could be determined. From this relationship, the average count rates in the potassium, uranium, and thorium windows were calculated.

A computer program PADWIN was used to derive the stripping ratios and window sensitivities (Løvborg et al., 1981). This program also calculates the standard deviations of the various calibration constants taking into consideration Poisson counting errors as well as uncertainties in the pad concentrations.

Table 14 compares the stripping ratios and sensitivities of the detector package Box 1 measured on the Uplands calibration pads using both the original concentrations and the new concentrations determined by portable gamma-ray spectrometry. The results show no significant difference between the two sets of calibration data. However, the errors in the calibration constants are significantly reduced using the new estimates of concentration but are still rather large, particularly for those calibration constants involving a window sensitivity to potassium. This was not unexpected since all five pads have very little potassium variation (Tables 12 and 13).

Experiments with transportable calibration pads

After the analysis of radioelement concentrations of the Uplands pads using the portable spectrometer, and the calibration of the airborne system using the revised concentrations, the airborne system was calibrated for comparison over the

Table 14. Comparisons of stripping ratios and sensitivities of Box 1

	Using original concentrations	Using new concentrations
α	0.291 ± 0.041	0.267 ± 0.020
β	0.400 ± 0.161	0.394 ± 0.048
γ	0.780 ± 0.265	0.743 ± 0.091
a	0.032 ± 0.138	0.011 ± 0.043
b	-0.164 ± 0.181	0.038 ± 0.054
g	0.158 ± 0.088	0.138 ± 0.050
K Sens (c/s/%)	94.4 ± 38.4	110.7 ± 24.4
U Sens (c/s/ppm)	8.15 ± 0.84	8.32 ± 0.65
Th Sens (c/s/ppm)	4.67 ± 0.40	4.58 ± 0.14

transportable pads. The stripping ratios for each of the three packages of four detectors were measured with the entire system in the Skyvan aircraft in its standard flying configuration.

The transportable pads were first mounted on a metal trolley so that they could easily be moved. The calibration was performed with all four pads in exactly the same position directly beneath the detector package by making use of fixed marks on the ground. Approximately fifteen minutes of one second spectra were recorded with all four pads beneath each of the three detector packages.

The average count rates in each radioelement window were determined for each of the sets of spectra, following the same procedure that had been used for processing the calibration data from the Uplands pads. The calibration program PADWIN was then used to derive the stripping ratios for the three detector packages (Løvborg et al., 1981). Only the stripping ratios were required from this calibration, as sensitivities for airborne systems are determined over a test line, as described previously. No geometric correction factor is required in determining stripping ratios, so the noninfinite nature of the transportable pads was not a problem.

Table 15 compares the six stripping ratios for all three detector packages using the Uplands pads with those from the transportable pads. For all three detector packages, no significant difference is found between the two sets of data. However, the stripping ratios obtained using the transportable pads have significantly smaller errors.

In using large aircraft pads for calibration, radiation is received not only from areas of the pad directly beneath the detectors but from all parts of the pad. The detected radiation therefore strikes the detectors at a variety of angles. Previous work by Grasty and Holman (1974) has shown that for large diameter cylindrical detectors the shape of the thorium gamma-ray spectrum shows some variation with the position of the source. Some small difference was therefore expected between the stripping ratios measured with the large aircraft size pads and the much smaller transportable pads. The fact that none was detected could be due to the large uncertainties associated with the measurements on the Uplands pads (Table 15).

These results suggested that stripping ratios could be accurately determined using transportable pads. There are many advantages in using transportable pads, notably low cost compared to large permanent pads, and elimination of the problems associated with moisture content variation in permanent pads exposed to the weather. Some further experiments were therefore carried out to confirm that small transportable calibration pads and large aircraft pads would give the same stripping ratios for large volume detector packages.

In the first experiment, uranium and thorium ores were sealed in flat 30 cm x 30 cm plastic bags to simulate thin sources of radiation with a minimum of scattering within the source. These sources were placed under the aircraft, directly beneath Box 2. Spectra were recorded from the ores as well as a background spectrum when the ores were removed. In addition to measuring spectra from the sources when they were directly underneath the detectors, spectra were also recorded with the uranium and thorium ores moved off to the side of the aircraft. In this position, the centre of the source is located at an angle of about 45 degrees from the central axis of the detector package.

From these measured spectra, the stripping ratios α, β, γ, and a could be determined from the background-subtracted uranium and thorium spectra. These results in Table 16 show that the thorium and uranium spectral shapes from thin sources are the same for the two positions and therefore unaffected by the angle the radiation strikes the detector.

An experiment was also carried out to see how the stripping ratios varied with the position of the small pads. In this experiment Box 2 was calibrated with the small pads in two different positions. The pads were first placed directly beneath the detector package, then moved 1 m to the side, i.e. one pad

Table 15. Comparison of stripping ratios using Uplands pads (new concentrations) and transportable pads

	BOX 1	
	Uplands	Transportable pads
α	0.2670 ± 0.0199	0.2597 ± 0.0024
β	0.3941 ± 0.0477	0.3550 ± 0.0049
γ	0.7429 ± 0.0911	0.8282 ± 0.0092
a	0.0114 ± 0.0429	0.0779 ± 0.0033
b	0.0380 ± 0.0543	-0.0036 ± 0.0066
g	0.1380 ± 0.0501	0.0172 ± 0.0031
	BOX 2	
	Uplands	Transportable pads
α	0.2583 ± 0.0204	0.2478 ± 0.0021
β	0.4099 ± 0.0462	0.3536 ± 0.0043
γ	0.6640 ± 0.0852	0.8105 ± 0.0077
a	0.0082 ± 0.0400	0.0732 ± 0.0026
b	0.0431 ± 0.0566	-0.0033 ± 0.0063
g	0.0724 ± 0.0575	0.0090 ± 0.0027
	BOX 3	
	Uplands	Transportable pads
α	0.2636 ± 0.0196	0.2604 ± 0.0053
β	0.4105 ± 0.0465	0.3447 ± 0.0108
γ	0.7060 ± 0.0923	0.8128 ± 0.0210
a	-0.0139 ± 0.0438	0.0749 ± 0.0088
b	0.0641 ± 0.0554	-0.0036 ± 0.0092
g	0.1099 ± 0.0530	0.0133 ± 0.0065

Table 16. Comparison of stripping ratios for Box 2 with thin sources below and offset

	Thin source below	Thin sources offset
α	0.225 ± 0.001	0.225 ± 0.003
β	0.302 ± 0.003	0.322 ± 0.011
γ	0.750 ± 0.005	0.734 ± 0.021
a	0.074 ± 0.001	0.082 ± 0.005

width, so that the radiation was striking the detectors at approximately 45 degrees. To ensure equivalent counting statistics, the counting period was twice as long when the pad was offset, 30 minutes compared to 15 minutes.

The results presented in Table 17 show that the stripping ratios have very similar values for the two different positions when the errors on the measurements are taken into consideration. Based on the thin source results (Table 16), this is to be expected. It should be noted that the difference between the thin source stripping ratios and those obtained from the small pads is due to Compton scattering within the pads. This is why point sources cannot be used for calibrating airborne and ground gamma-ray spectrometers.

An aircraft calibration pad can be considered to be made up of many small pads. It has been shown that the stripping ratios were unchanged when the small pads were moved 1 m to the side of the detector, proving that pads 1 m x 1 m will give the same stripping ratios as those that are 3 m x 3 m. Aircraft calibration pads are usually 8 m x 8 m, but a high proportion of the gamma rays detected originate in the area closest to the detector. It is therefore reasonable to expect, based on the experiment of offsetting the small pads by 1 m, that any difference in stripping ratios determined using large or small pads would be negligible. This conclusion is supported by the results in Table 15, obtained over the Uplands pads. Small calibration pads, with their advantages of low cost and stable moisture content, can therefore be used with confidence to determine the stripping ratios of airborne systems.

Aircraft calibration — practice

In the previous section we have shown that small transportable pads can be used to determine the stripping ratios of large volume airborne gamma-ray spectrometers. In this section we describe how the calibration should be performed and discuss some of the practical problems.

The Geological Survey of Canada (GSC) airborne gamma-ray spectrometer has three separate detector boxes of approximately 16.4 L (1000 cubic inches). In calibrating on large pads, each one of these boxes is calibrated separately because of the high count rates and possible pulse pile-up problems that can distort the gamma-ray spectrum compared to the spectrum at survey altitude where the count rates are much lower (Grasty, 1987).

Table 17. Stripping ratios for Box 2 with transportable pads below and offset

	Pads below	Pads offset
α	0.2478 ± 0.0021	0.2529 ± 0.0028
β	0.3536 ± 0.0043	0.3448 ± 0.0058
γ	0.8105 ± 0.0077	0.8151 ± 0.0108
a	0.0732 ± 0.0026	0.0638 ± 0.0043
b	-0.0033 ± 0.0063	-0.0091 ± 0.0071
g	0.0090 ± 0.0027	0.0043 ± 0.0036

With small calibration pads, it is not physically possible to calibrate all detector packages in an aircraft at the same time even if there were no problems of pulse pile-up. Each detector package of the GSC airborne system is calibrated with the system in the aircraft in its normal flying configuration. The four transportable pads are mounted on small trolleys that can be moved by hand under each of the detector packages. Instead of constructing special trolleys, a small pallet truck could be used.

The spectrometer is first tuned using a cesium-137 source placed underneath each detector package. The high voltage of each detector is adjusted so that the cesium-137 photopeak at 662 keV falls in channel 55 and each channel covers an energy range of 12 keV. The potassium, uranium, thorium, and total count windows will then be in their correct position provided there is a linear relationship between channel position and channel energy.

Each block is positioned directly under the box being calibrated and measurements are recorded for 10 minutes. With the GSC Skyvan aircraft, there is just enough room for the blocks on their trolleys. The top of each block is approximately 60 cm below the centre of each detector package. Each block is placed in exactly the same position under each detector package so that the background radiation is the same for all four blocks. The four series of measurements for the four pads are repeated for all three detector packages.

The computer program PADWIN described in Appendix D is used to determine the stripping ratios of each detector package. The geometric correction factor used in the program has no effect on the stripping ratios because this factor is only applied to the sensitivities. For the GSC system, the stripping ratios used for the entire system of three detector boxes are the average stripping ratios of all three individual boxes. In theory, the stripping ratios should be the weighted average of all three boxes, with the weighting being proportional to the sensitivity of a particular box. This sensitivity could be determined simply from measurements of the window count rates of the individual boxes over a uniformly radioactive ground. Normally, if the detectors are working properly and the system has been tuned correctly, the sensitivities and stripping ratios of each standard package of four prismatic detectors will be the same.

If the transportable pads do not fit under the aircraft, alternative procedures have to be considered. There are several alternatives:

1) All aircraft have jacking points so that the aircraft can be jacked up to check the undercarriage. The aircraft would only need to be raised at most 15 cm so that the calibration pads would fit underneath.

2) Even though the pads may not fit directly under the aircraft, it may be possible to put them beside the aircraft, close to a detector package. We have shown (Table 17) that the same stripping ratios are obtained when the calibration pads are placed directly underneath the detector package and off to the side. However, because of the reduced count rates when the pads are not directly under the detectors, the counting time should be increased to minimize any statistical errors.

3) Another alternative is to calibrate each box separately while it is outside the aircraft on some sort of structure under which the pads could be placed. Table 18 compares the stripping ratios of Box 1 with the system in the aircraft and on a heavy duty metal trolley that is used to store the GSC spectrometer. The values of the six stripping ratios are almost exactly the same for the two configurations. This is because the aircraft structure has only a minimal effect on the stripping ratios.

4) Another alternative procedure is to install the pads permanently in the ground with their top surface at ground level. The pads can then be used like standard aircraft pads. With such small pads, it is difficult, though not impossible, to manoeuvre the aircraft into the correct position to calibrate each detector package individually. There is also the problem of changes in the moisture content of the pads and associated gamma-ray fluctuations if the pads are exposed to the weather.

After the stripping ratios have been determined for the entire system, a test strip must be used to determine the height attenuation coefficients and the aircraft sensitivities at survey altitude. The transportable pads can be used to calibrate a portable spectrometer for use in measuring the radioelement concentration of the test strip. The aspect of the calibration involving measurements over a test strip is a standard procedure and is summarized in a technical report by the International Atomic Energy Agency (IAEA, in press).

Table 18. Stripping ratios of Box 1 on a trolley and in the Skyvan

	On a trolley	In the skyvan
α	0.2658 ± 0.0031	0.2597 ± 0.0024
β	0.3615 ± 0.0062	0.3550 ± 0.0049
γ	0.8197 ± 0.0107	0.8282 ± 0.0092
a	0.0593 ± 0.0041	0.0779 ± 0.0033
b	-0.0069 ± 0.0065	-0.0036 ± 0.0066
g	0.0124 ± 0.0034	0.0172 ± 0.00031

RADIATION DOSE DUE TO TRANSPORTABLE PADS

It has been the experience of many institutions that the general public is frequently concerned about the radioactivity of calibration pads. It is commonly believed that because the pads are used for calibrating radiation measuring equipment they must be a radiation hazard. However this is not the case. The pads are designed for calibrating equipment used to measure natural background radiation levels and for this reason the pads have levels of radioactivity comparable to those that are found naturally. In this section, the radiation from the calibration pads is shown to be significantly lower than the limit set by radiation protection authorities.

Terminology and dose relationships

Units of radioactivity can be confusing even to the practising health physicist. In this section the various units are explained in a straightforward manner which is hoped will be clear to the average scientific reader who is not a specialist in the field of radioactivity.

For almost all fields of science a unit of a physical measurement such as temperature, density, etc. uniquely defines a particular property of a material. An ionizing radiation field, however, cannot in general be defined uniquely since it can consist of radiation with a complete range of energies and angular distributions. One way of comparing radiation fields is by means of an ionization chamber which measures the quantity of electrical charge released in a gas through absorption of the radiation. This type of measurement is most useful for the health physicist since it may be related to the physical damage that will occur in living cells.

The radiation intensity at a given place is termed its "Exposure" (E) and is measured by its ability to produce ionization at that place. The unit of exposure is the roentgen (R). One roentgen is defined as the quantity of X radiation or gamma radiation that produces one electrostatic unit of charge of either sign in 1 mL of air at standard temperature and pressure.

In 1956 a unit of radiation, which applied to any form of ionizing radiation, was adopted. This unit of "absorbed energy" or "dose" is the energy imparted by ionizing radiation to 1 g of any material, at the particular point of interest. The unit of absorbed dose is the "rad" (radiation absorbed dose) which is the deposition of an energy of 100 ergs per gram. In expressing the absorbed dose, the particular absorbing material under consideration must always be given.

Environmental radiation measurements are normally presented as absorbed dose rates in air or as exposure rates. The relation between the air absorbed dose rate (D_a) and exposure rate is given by:

$$D_a = aE \qquad (33)$$

where a has the value 0.869 rad/R.

The health physicist is concerned with radiation dose absorbed by the body. Exposure may be converted directly to absorbed dose through the use of a simple conversion factor as in equation (33).

This factor takes into consideration the gamma-ray energy distribution as well as the geometry and attenuation characteristics of the body. O'Brien (1978) has calculated the conversion factors between exposure and absorbed dose for various organs and tissues of the body. The relationship between exposure and whole-body dose (D), measured in rads, is given by:

$$D = 0.6E \quad (34)$$

The dose to the red bone marrow, lungs, and gonads, which are generally of interest to the health physicist, can be calculated using the same conversion factor of 0.6 rad/R.

Different types of radiation cause different effects in biological tissues. For this reason, in comparing the effects of radiation on living systems, a derived unit, the "rem" (roentgen equivalent man) is used. One rem is the dose from any radiation that produces biological effects in man equivalent to one rad of X-rays. The dose in rems is the product of the dose in rads and a factor called the quality factor which depends on the Relative Biological Effectiveness (RBE) of the radiation concerned. This unit of dose is commonly called the dose-equivalent (D.E.). Therefore

$$\text{D.E. (rems)} = \text{RBE} \times \text{rads} \quad (35)$$

Gamma rays, which are the principal concern in this report, have an RBE value of 1.

In recent years quantities used in radiation protection have more commonly been expressed in SI units. These units are the Gray (Gy) and the Sievert (Sv).

The Gray is the unit of absorbed dose corresponding to the rad and is the energy imparted by ionizing radiation to material corresponding to one joule per kilogram. The relation between the Gray and the rad is:

$$1\ \text{Gy} = 100\ \text{rad} = 1\ \text{J/kg} \quad (36)$$

The Sievert is the SI unit for dose equivalent corresponding to the rem, the relation being given by

$$1\ \text{Sv} = 100\ \text{rem} \quad (37)$$

Dose calculations

Løvborg (1984) has compared the measured and calculated radiation exposure rates at calibration facilities in the United States and in Sweden. He found that the exposure rates on the calibration pads could be predicted reliably from the size of the pads and their radioactive concentrations. Using Løvborg's published data, we have determined the exposure rate at the surface of the transportable pads for each of the three radio-elements.

These values are:

$$1\ \text{pct K} = 1.18\ \mu\text{R/hr} \quad (38)$$

$$1\ \text{ppm eU} = 0.498\ \mu\text{R/hr} \quad (39)$$

$$1\ \text{ppm eTh} = 0.221\ \mu\text{R/hr} \quad (40)$$

Based on the concentrations of potassium, uranium and thorium of the pads (Table 8), the exposure rates at the surface of the pads are calculated to be:

K-PAD: $7.57 \times 1.18 + 1.22 \times 0.498 + 1.40 \times 0.221 = 9.80\ \mu\text{R/hr}$

U-PAD: $1.07 \times 1.18 + 46.93 \times 0.498 + 2.75 \times 0.221 = 25.24\ \mu\text{R/hr}$

T-PAD: $1.43 \times 1.18 + 1.74 \times 0.498 + 121.6 \times 0.221 = 29.43\ \mu\text{R/hr}$

Scientists and medical doctors from international agencies responsible for radiation protection throughout the world have set an annual radiation dose-equivalent of 5 mSv (500 mrem) as a safe maximum dose for a member of the general public. It has been estimated that the average annual Canadian radiation dose from all sources of natural radiation is 690μ Sv (69 mrem) (Grasty et al., 1984).

Using equation (34), a person in direct contact with the thorium pad, which gives the highest radiation level, will receive a dose-equivalent of 17.7 (0.6 x 29.43) μ rem/hr or 0.177 μ Sv/hr. If this person spends an entire year, day and night, directly in contact with the thorium pad, he will receive an additional radiation dose from the thorium pad of 1.55 mSv or 155 mrems per year. This radiation dose-equivalent is well below the permissible level of 5 mSv (500 mrem) and comparable to the annual dose-equivalent from all natural sources.

In view of the fact that it is quite unreasonable to assume that a person may spend an entire year in contact with the pads, and that the radiation from the pads is virtually undetectable a few metres from the pads, the radiation dose due to the pads can be considered negligible.

SUMMARY AND CONCLUSIONS

Sets of four transportable pads 1 m x 1 m x 30 cm, each pad weighing approximately 675 kg and mounted on a wooden pallet, were constructed for calibrating portable gamma-ray spectrometers. The design of the pads was optimized using a computer modelling program to give the maximum count rate for the particular weight of the pads.

The background pad was manufactured with low radioactivity quartz sand and limestone aggregate. The potassium pad was made with hand-picked potassium feldspar that had very low concentrations of uranium and thorium. An ideal source of thorium for the thorium pad was found to be a rare earth phosphate called britholite associated with the Oka carbonatite complex near Montreal, Quebec. This thorium ore has a thorium/uranium ratio of 127:1 and was selected by the International Atomic Energy Agency as the thorium counting standard for laboratory gamma-ray spectrometers.

Initially, the uranium pads were manufactured using a uranium ore from Beaverlodge, Saskatchewan that was known to be a low emanator of radon. However, soon after construction, the uranium pads were found to lose their gamma-ray activity due to a breakdown of the uraninite grains by the alkali gels in the concrete. Efforts to seal the pads with a polyester resin sealer or with water-based acrylic latex were only partially successful. New uranium pads were then made using a uranium-bearing ceramic-like calcium

silicate slag from a phosphorus processing plant. This material proved to be ideal. Tests showed it to be a low emanator of radon both in its initial state and when used in concrete.

Laboratory gamma-ray measurements were carried out on sliced concrete samples poured into cardboard cylinders during the pad construction. These samples were allowed to dry naturally, thereby being representative of the pads in their natural state.

Homogeneity measurements carried out on the surface of the potassium, uranium, and thorium pads using a shielded portable gamma-ray spectrometer showed that any inhomogeneities in the pads were small. Because the pads were homogeneous, the laboratory measurements could be used to assign reliable radioactive concentrations to the pads.

In using the pads for the calibration of portable gamma-ray spectrometers, a geometric correction factor must be applied to the spectrometer sensitivities because of the noninfinite size of the pads. These geometric correction factors were derived for each spectrometer window and were based on the distance of the centre of the detector from the pad surface and various other known physical characteristics of the pads.

A computer program was used to estimate the errors in the calibration constants of a typical portable gamma-ray spectrometer due to Poisson counting statistics and uncertainties in the concentrations of the pads. For a counting time of 10 minutes on each pad, it was found that errors in the calibration constants were extremely small because the pads provide almost pure gamma-ray spectra of the three radioelements and their concentrations were reliably known.

A portable gamma-ray spectrometer calibrated on the transportable pads was used to improve the accuracy in the measurements of the potassium, uranium, and thorium concentration of the large aircraft calibration pads at Uplands airport, Ottawa. The improved reliability in these measurements significantly increased the accuracy in the calibration constants of the airborne system.

Calibration experiments showed that for a large volume airborne system, the potassium, uranium, and thorium spectra had the same shape from the transportable pads and from the large aircraft pads. The small transportable pads can therefore be used for calibrating large volume airborne systems as well as portable gamma-ray spectrometers. Small transportable pads appear to be an effective and inexpensive way of calibrating both ground and airborne gamma-ray spectrometers.

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APPENDIX A

Computation of calibration factors (matrix method)

Pad	K - Window Counts/min.	U - Window Counts/min.	T - Window Counts/min.
K - Blank	1058.3	1.6	-6.0
U - Blank	542.0	843.3	19.8
T - Blank	439.9	472.7	785.1

COUNT MATRIX = SENSITIVITY MATRIX x CONCENTRATION MATRIX
(Blank Pad Removed) (Blank Pad Removed)

	WINDOW COUNTS/MIN. K	U	T		WINDOW SENSITIVITIES				PAD CONCENTRATIONS		
K-Pad	1058.3	1.6	-6.0		$s_{1,1}$	$s_{1,2}$	$s_{1,3}$		6.14	0.28	-0.92
U-Pad	542.0	843.3	19.8	=	$s_{2,1}$	$s_{2,2}$	$s_{2,3}$	x	-0.36	45.99	0.43
T-Pad	439.9	472.7	785.1		$s_{3,1}$	$s_{3,2}$	$s_{3,3}$		0	0.80	119.28

where sensitivity matrix S = (for small sources)

172.3	0.0	-0.01
13.1	18.3	0.37
3.60	3.84	6.58

Stripping ratios are given by:

$\alpha = s_{3,2}/s_{3,3} = 3.84/6.58 = 0.584$
$\beta = s_{3,1}/s_{3,3} = 3.60/6.58 = 0.547$
$\gamma = s_{2,1}/s_{2,2} = 13.1/18.3 = 0.716$
$a = s_{2,3}/s_{2,2} = 0.37/18.3 = 0.020$
$b = s_{1,3}/s_{1,1} = -0.01/172.3 = 0.0$
$g = s_{1,2}/s_{1,1} = 0.0/172.3 = 0.0$

Infinite source sensitivities* are given by:

K Sens. = $s_{1,1} \times g_K = 172.3 \times 1.16 = 199.9$ counts/min/%K
U Sens. = $s_{2,2} \times g_U = 18.3 \times 1.17 = 21.4$ counts/min/ppm eU
T Sens = $s_{3,3} \times g_{Th} = 6.58 \times 1.19 = 7.83$ counts/min/ppm eTh

* The infinite source sensitivities are derived from the calculated sensitivities for small pad size sources using the geometric correction factors given in Table 10.

APPENDIX B

Hewlett-Packard 15-C program to calibrate a portable spectrometer on the transportable pads

PROBLEM: To solve matrix equation given in Appendix A

$$\underset{A}{\text{COUNT MATRIX}} = \underset{B}{\text{SENSITIVITY MATRIX}} \times \underset{C}{\text{CONCENTRATION MATRIX}}$$

KEY STROKES	DISPLAY	COMMENTS
3 ENTER f DIM A	3.0000	Dimension matrix A to be 3 x 3
f USER	3.0000	Prepares for automatic entry of
f MATRIX 1	3.0000	matrix elements.
1058.3 STO A	A 1,1	Denotes matrix A, row 1, column 1
	1058.3	Store $a_{1,1}$ K window counts (K - B pad)
1.6 STO A	1.6	Store $a_{1,2}$ U window counts (K - B pad)
6.0 CHS STO A	-6.0	Store $a_{1,3}$ T window counts (K - B pad)
542.0 STO A	542.0	Store $a_{2,1}$ K window counts (U - B pad)
843.3 STO A	843.3	Store $a_{2,2}$ U window counts (U - B pad)
19.8 STO A	19.8	Store $a_{2,3}$ T window counts (U - B pad)
439.9 STO A	439.9	Store $a_{3,1}$ K window counts (T - B pad)
472.7 STO A	472.7	Store $a_{3,2}$ U window counts (T - B pad)
785.1 STO A	785.1	Store $a_{3,3}$ T window counts (T - B pad)
3 ENTER f DIM C	3.0000	Dimension matrix C to be 3 x 3
6.14 STO C	C 1,1	Denotes matrix C, row 1, column 1
	6.14	Store $c_{1,1}$ K concentration (K - B pad)
0.28 STO C	0.28	Store $c_{1,2}$ U concentration (K - B pad)
0.92 CHS STO C	-0.9	Store $c_{1,3}$ T concentration (K - B pad)
0.36 CHS STO C	-0.36	Store $c_{2,1}$ K concentration (U - B pad)
45.99 STO C	45.99	Store $c_{2,2}$ U concentration (U - B pad)
0.43 STO C	0.43	Store $c_{2,3}$ T concentration (U - B pad)
0 STO C	0	Store $c_{3,1}$ K concentration (T - B pad)
0.80 STO C	0.80	Store $c_{3,2}$ U concentration (T - B pad)
119.28 STO C	119.28	Store $c_{3,3}$ T concentration (T - B pad)
f RESULT B	119.28	Set up matrix B for storing results
RCL MATRIX A	A 3 3	Recall A - 3 x 3 matrix
RCL MATRIX C	C 3 3	Recall B - 3 x 3 matrix
÷	Running	Indicates $C^{-1}A$ is being calculated
	B 3 3	Dimensions of the result matrix B
RCL B	172.3	$b_{1,1}$ K window sensitivity to K
RCL B	0.00	$b_{1,2}$ U window sensitivity to K
RCL B	-0.01	$b_{1,3}$ T window sensitivity to K
RCL B	13.1	$b_{2,1}$ K window sensitivity to U
RCL B	18.3	$b_{2,2}$ U window sensitivity to U
RCL B	0.37	$b_{2,3}$ T window sensitivity to U
RCL B	3.60	$b_{3,1}$ K window sensitivity to T
RCL B	3.84	$b_{3,2}$ U window sensitivity to T
RCL B	6.58	$b_{3,3}$ T window sensitivity to T

APPENDIX C

Specifications of transportable calibration pads

Dimensions 1 m x 1 m x 30 cm

Weight
- B-PAD 680 kg
- K-PAD 670 kg
- U-PAD 670 kg
- T-PAD 680 kg

Density
- B-PAD 2.28 g/cm^3
- K-PAD 2.23 g/cm^3
- U-PAD 2.24 g/cm^3
- T-PAD 2.28 g/cm^3

Composition
- B-PAD: Standard concrete with 3/8 inch limestone aggregate.
- K-PAD: Feldspar crushed to -3/4 inch with cement in the ratio 4 feldspar to 1 cement.
- U-PAD: Concrete with 3/8 inch limestone aggregate + phosphate slag crushed to -1/4 inch
- T-PAD: Concrete with 3/8 inch limestone aggregate + thorium ore crushed to -20 +100 mesh.

Percent of infinite source

- K-PAD 86.5% for 1.46 MeV potassium gamma rays.
- U-PAD 85.8% for 1.76 MeV uranium gamma rays.
- T-PAD 84.2% for 2.62 Mev thorium gamma rays.

Concentrations of Transportable Pads

	K(%)	U(ppm)	Th(ppm)
B-PAD	1.43 ± 0.01	0.94 ± 0.02	2.32 ± 0.06
K-PAD	7.57 ± 0.05	1.22 ± 0.09	1.40 ± 0.12
U-PAD	1.07 ± 0.01	46.93 ± 0.32	2.75 ± 0.07
T-PAD	1.43 ± 0.02	1.74 ± 0.16	121.6 ± 1.66

Errors are at the one sigma level.

APPENDIX D

Program PADWIN

The calibration program called PADWIN was originally written by Leif Løvborg and his associates at the Riso National Laboratory in Denmark. The program has been modified to allow for the noninfinite size of the transportable pads. It has the advantage over the Hewlett Packard 15-C program in Appendix B that the calibration constants and their associated errors are both calculated. These errors take into consideration Poisson counting errors as well as uncertainties in the concentrations of the pads.

The program is in executable form for an IBM-PC or AT compatible computer and will run with or without a math coprocessor. In order to modify the program for particular needs, the Fortran listing PADWIN.FOR has also been included. Two data files that are used by the program are also on the disc. The file COUNTS.DAT has the recorded count data. The file STANDARD.DAT has the pad concentration data as well as the geometric correction factors shown in Table 10. The count and concentration data for the calibration being processed must be placed in these files before running PADWIN.

The example data in COUNTS.DAT is the same as used in Appendix A and B for a typical 7.6 cm x 7.6 cm (3 inch x 3 inch) sodium iodide detector. This should be replaced by the following data for any new calibration being processed:

1) title,
2) number of pads,
3) counting time in minutes on the Blank Pad,
4) accumulated counts in the K-window on the Blank Pad,
5) accumulated counts in the U-window on the Blank Pad,
6) accumulated counts in the T-window on the Blank Pad.

Repeat sequence of counting time and window counts for the potassium, uranium, and thorium pads.

The format and contents of STANDARD.DAT file are self-evident, being the concentrations of the four pads, the errors in the concentrations, and the geometric correction factors as given in Table 10.

PADWIN first calculates the potassium, uranium, and thorium window sensitivities for small pad-size sources from the count and concentration data. The geometric correction factors are then applied to these small source sensitivities to give infinite source sensitivities.